Observations and Modeling of Low-Altitude Ionospheric Responses to the 2017 September X8.2 Solar Flare at Mars

Shaosui Xu$^1$, Ed Thiemann$^2$, David Mitchell$^1$, Frank Eparvier$^2$, David Pawlowski$^3$, Mehdi Benna$^4$, Laila Andersson$^2$, Michael W. Liemohn$^5$, Stephen Bougher$^5$, Tom Woods$^2$, Phil Chamberlin$^2$, Sonal Jain$^2$, Christian Mazelle$^6$

$^1$Space Sciences Laboratory, University of California, Berkeley, USA
$^2$Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado, USA
$^3$Physics Department, Eastern Michigan University, Ypsilanti, Michigan, USA
$^4$NASA Goddard Space Flight Center, Greenbelt, Maryland, USA
$^5$Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, Michigan, USA
$^6$IRAP, CNRS - University of Toulouse - UPS - CNES, Toulouse, France
Introductions & Motivation

• Main source of dayside ionosphere at Mars:
  • Solar EUV (10-100 nm), creating M2 layer
  • X-ray (< 10 nm), creating M1 layer

• Dayside ion production mainly comes from two processes:
  I. Initial photoionization from photons, creating ions and photoelectrons
  II. Electron impact ionization (EII) by photoelectrons

• Solar EUV and X-ray irradiance vary orders of magnitude during a flare, causing variations in ionosphere/thermosphere
  • September 10, 2017, MAVEN encountered the largest flare (X8.2) to date
  • Characterizing ionosphere variation
Methodology

• Characterizing low-altitude ionospheric response to this flare with SuperThermal Electron Transport (STET) model:
  • Modeling photoelectron flux variations
  • Calculating photoionization rate and EII rate for ion production
  • Assuming photochemical equilibrium (PCE, <200 km): obtain $O_2^+$ and $CO_2^+$ densities

• STET solves superthermal electron flux $\psi$ in time (t), spatial distance along a single magnetic field (s), electron energy ($E$), and pitch angle $\mu$:

$$\frac{\beta E}{\sqrt{E}} \frac{\partial \psi}{\partial t} + \mu \frac{\partial \psi}{\partial s} - \frac{1 - \mu^2}{2} \left( -\frac{F}{E} + \frac{1}{B} \frac{\partial B}{\partial s} \right) \frac{\partial \psi}{\partial \mu} + EF \mu \frac{\partial}{\partial E} \left( \frac{\psi}{E} \right) = Q + S_{ee} + \sum_{\alpha} (S_{e\alpha} + S_{e\alpha}^* + S_{e\alpha}^+) + \sum_i (S_{el} + S_{el}^* + S_{el}^-)$$
Methodology

- Overview of the flare event
- Three periods are selected: pre-flare, peak-flare, post-peak flare

Fang+ (2018)
Methodology

• EUV inputs to STET:
  • EUV spectra from a spectral model [Thiemann et al., 2018], similar to FISM
Methodology

• Main inputs to STET:
  • O and CO$_2$ density from NGIMS (Neutral Gas and Ion Mass Spectrometer) & MGITM (Mars-Global Ionosphere Thermosphere Model) for below and above MAVEN periapsis, respectively
  • Te from LPW (Langmuir Probe and Waves), extrapolated to neutral Tn at 115 km from MGITM

• Only TWO Neutral and thermal plasma available:
  • Pre-flare and peak-flare: pre-flare profiles
  • Post-peak flare: post-peak profiles
Data-Model Comparison of Photoelectron Spectra

- **Thick** black and **blue** energy spectra from SWEA (Solar Wind Electron Analyzer) observations
- Thin black, **blue**, and **red** energy spectra from STET modeling
- Typical ionospheric photoelectron spectral features: He-\(\text{II}\) peak, knee, O Auger peak
- Mostly in good agreement
  - Within 30% for < 60 eV and 200-500 eV
  - Modeled solar irradiance spectra are very accurate for EUV & X-ray \(\sim 17-60\) nm, 1-6 nm, correspondingly
Data-Model Comparison of Photoelectron Spectra

• Auger electrons
  • Soft X-ray ionizing inner-shell electrons of C, O, N
  • Resultant ions deexciting through emitting Auger electrons
  • At fixed energies: C~250 eV, N~360 eV, O~500 eV

• C Auger electron peak in both modeled and observed photoelectron spectra
  • Being consistently observed over 4 min during this flare event
A Clearer Example of Carbon Auger Electrons From SWEA

This provides a clear and unambiguous identification of the carbon Auger peak in the electron energy spectra in the Martian ionosphere for the first time.
Observations and Modeling of Plasma Densities

• Ion Densities calculated assuming photochemical equilibrium:

\[ \begin{align*}
R1: & \quad \text{CO}_2 + h\nu \rightarrow \text{CO}_2^+ + e \quad \text{[STET]} \\
R2: & \quad \text{CO}_2^+ + \text{O} \rightarrow \text{CO} + \text{O}_2^+; \quad k_2 = 1.64 \times 10^{-10} \\
R3: & \quad \text{CO}_2^+ + \text{O} \rightarrow \text{CO}_2 + \text{O}^+; \quad k_3 = 9.6 \times 10^{-11} \\
R4: & \quad \text{O}^+ + \text{CO}_2 \rightarrow \text{O}_2^+ + \text{CO}; \quad k_4 = 1.1 \times 10^{-9} \\
R5: & \quad \text{CO}_2^+ + e \rightarrow \text{CO} + \text{O}; \quad k_5 = 4.2 \times 10^{-7} \left(\text{300/Te}\right)^{0.75} \\
R6: & \quad \text{O}_2^+ + e \rightarrow \text{O} + \text{O}; \quad k_6 = 2.4 \times 10^{-7} \left(\text{300/Te}\right)^{0.7} \\
\end{align*} \]

\[ \begin{align*}
\text{CO}_2^+ + \text{O} \rightarrow \text{O}_2^+ + \text{CO} \\
\text{Source for } \text{O}_2^+ \\
\text{Loss for CO}_2^+, \text{ depending on } n(\text{O}) \\
\end{align*} \]

\[ \text{Schunk and Nagy [2009]} \]

• From R1-R6, we can obtain:

\[ n(\text{O}_2^+) = \sqrt{\frac{(k_2 + k_3)n(\text{CO}_2^+)n(\text{O})}{k_6}} \quad (\text{R2, R3, R4, R6}) \]

\[ n(\text{CO}_2^+) = \frac{P(\text{CO}_2^+)}{(k_2 + k_3)n(\text{O}) + k_5n(\text{O}_2^+)} \quad (\text{R1, R2, R3, R5}) \]
Observations and Modeling of Plasma Densities

- From model:
  - Solid lines: CO2+ and O2+ densities for 3 periods

- From observations:
  - LPW e- density (*1.4) and NGIMS CO2+ density (*4) for pre-flare and post-peak flare, inbound and outbound
Observations and Modeling of Plasma Densities

- Comparison of modeled ion densities and observations:
  - Modeled $O_2^+$ densities ~40% higher than LPW e- density, reasonable agreement
  - Modeled $CO_2^+$ densities ~4x NGIMS $n(CO_2^+)$
  - The relative enhancement are similar, comparing MAVEN and model results
  - Similar scale heights from MAVEN and model
Observations and Modeling of Plasma Densities

- Relative density enhancement to the pre-flare period from modeling:
  - **Peak-flare/pre-peak**
    - atmosphere profiles kept the same
    - $N(O_2^+)$: ~15% increase for M2 layer and up to ~300% for M1 layer; ~$\sqrt{\text{prod. rate}}$
    - $N(CO_2^+)$: ~35% increase for M2 layer and up to ~1500% for M1 layer; ~$\text{prod. Rate}$
  - **Post-peak flare/pre-peak**
    - thermosphere expansion modulates ion enhancements
    - $N(O_2^+)$: <50% enhancement
    - $N(CO_2^+)$: <50% enhancement above 140 km; *decrease* below 140 km due to enhanced O density (loss rate)
Summary

• Modeling low-altitude ionospheric response to X8.2 flare with STET

• Found a good agreement between modeled (STET) and measured (SWEA) photoelectron spectra, meaning small errors in modeled EUV/X-ray spectra

• First clear and repeated identification of the carbon Auger peak in the Martian ionosphere

• Comparing pre-flare and **flare peak**, for the same atmosphere profiles, the modeled $\text{O}_2^+$ and $\text{CO}_2^+$ densities are increased by 15% and 35% above the M2 peak and up to 300% and 1500% at 100 km, respectively

• Comparing pre-flare and **post-peak flare period**, $\text{O}_2^+$ and $\text{CO}_2^+$ density enhancement < 50%, consistent with MAVEN observations, due to a combination of increased EUV fluxes and also neutral atmosphere expansion
  • A higher O density during the flare actually results in decreases in $\text{CO}_2^+$ density below 140 km
MAVEN Instruments

**Suprathermal e- (photoelectron) measurements**

Ne, Te

**Solar Inputs**
- LPW
- SEP
- SWIA
- SWEA
- MAG

**EUVM:**
- 0-7 nm, 17-22 nm, 121-122 nm, 3 bands
- Drive an irradiance model

**Plasma Processes**
- LPW
- SWIA
- STATIC
- SWEA
- MAG
- IUVS

**Neutral Processes**
- Neutral densities (O, CO2)
- Ion density (CO2+)

**Neutral Processes**
- NGIMS
- IUVS
Methodology

• Main inputs to STET:
  • O and CO₂ density from NGIMS (Neutral Gas and Ion Mass Spectrometer) & MGITM (Mars-Global Ionosphere Thermosphere Model)
  • Te from LPW (Langmuir Probe and Waves), extrapolated to neutral Tn at 115 km from MGITM

• Only TWO Neutral and thermal plasma available:
  • Pre-flare and peak-flare (the same): pre-flare MAVEN measurements and MGITM results
  • Post-peak flare: post-peak MAVEN measurements and MGITM results
Observations and Modeling of Plasma Densities

- Relative enhancement in total production (photoi + EII):
  - Peak flare/pre-flare: increased 40% above 130 km and up to 1500% down below 130 km (same atmosphere)
  - Post-peak flare/pre-flare: < 200% due to enhanced solar irradiance and expanded thermosphere
Data-Model Comparison of Photoelectron Spectra

(b) Quantitative comparison:
- Within 30% for $< 60$ eV and 200-500 eV, roughly corresponding to EUV & X-ray ~17-60 nm, 1-6 nm
Observations and Modeling of Plasma Densities

- Production rates for $\text{CO}_2^+$:
  - PHI (photoionization): dashed lines
    - peaks $\sim$125 km from pre-flare and peak-flare, as the two using the same background profiles
    - peaks $\sim$135 km for post-peak, due to expanded thermosphere
  - EII (electron impact ionization): solid lines
    - peaks deeper, from pre-peak, post-peak flare to peak-flare, as the soft X-ray spectrum becomes harder

- Relative enhancement in total production (PHI + EII):
  - Peak flare/pre-flare: increased 40% above 130 km and up to 1500% down below 130 km (same atmosphere)
  - Post-peak flare/pre-flare: < 200% due to enhanced solar irradiance and expanded thermosphere
Observations and Modeling of Plasma Densities

• The M2 layer peaks ~ 125 km for O2+ and ~140—150 km for CO2+

• A shoulder from the M1 layer is seen in O2+ profile for the post-peak flare period, but not for the pre-flare and peak-flare periods
  • Whether M1 and M2 peaks are well separated depends on solar spectral shapes and neutral density profiles